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Observation of internal electric charge in InP self-assembled quantum dots

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Abstract. Heterostructures with InP self-assembled quantum dots were studied. Strong Franz-Keldysh oscillations were found in their nonlinear reflection spectra. These oscillations manifest the presence of built-in electric field. The field originates from electric charge gathered by dots during the growth process.

Introduction

Self assembled quantum dots (SAD) are recently a subject of the extensive study [1–5]. It is attractive to make an ensemble of quantum dots (QDs) in the single growth process. This is considered to prevent QDs surface from strong contamination. Nevertheless the structure and properties of the interface between SAD and barrier layers are still in question. Due to the small size of the dots, a fraction of surface atoms to volume atoms is relatively large. The lattice mismatch between materials of QDs and barrier layers gives rise to stresses and strains around the QDs.

In this work we studied InP self assembled QDs grown by gas source molecular beam epitaxy (GS MBE) technology. We used pump-probe method for the study of a nonlinear part of reflection and its dependence on a laser wavelength. It is found that the QD layer posesses a large amount of presumably negative electric charge. We suppose that this charge is caught by the acceptors located at the interfaces between InP QD layer and InGaP barrier layers.

1 Experimental

The heterostructures were grown on n^+ GaAs (100) substrates. Their simplified structure is shown in the inset of Fig. 1. The thickness of the barrier layers is 1000 Å for a sample QDP1779 and 1500 Å for a sample QDO1505 which were studied most thoroughly. An example of PL spectrum is shown in Fig. 1.

The experiments were carried out on the setup which includes a femtosecond Ti:sapphire laser "Tsunami" (power source "Millenia", frequency 82 MHz, pulse duration 0.1–1 ps) which is tunable from about 0.7 to 0.85 μm. Amplitude modulation of the pump and probe beams at different frequencies, optical phase shift between them and lock-in detection of the signal at the differential frequency let us to avoid noises from

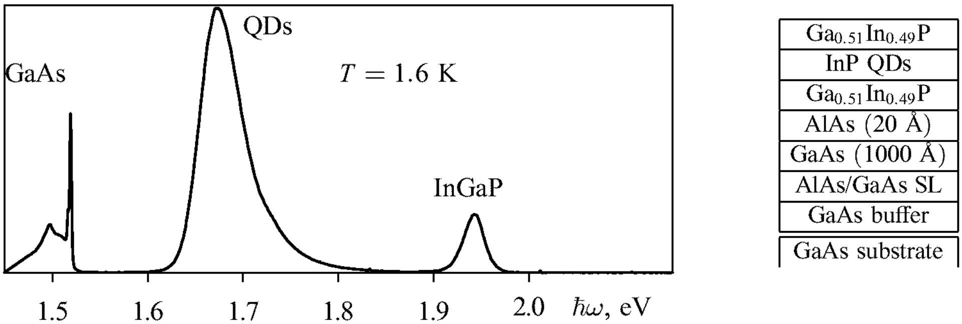

Fig 1. PL spectrum of sample QDO1505. "QDs", "InGaP", and "GaAs" mark accordingly PL of QDs and barrier and buffer layers excitons. Inset: structure of the studied samples.

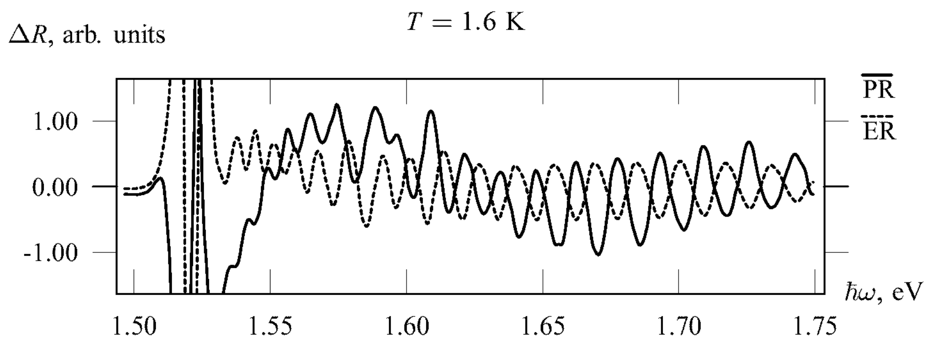

Fig 2. Pump-probe (PR) and electroreflection (ER) spectra of sample QDP1779.

the scattered light and achieve excellent sensitivity of detection of nonlinear reflection whose detection limit is about 10^{-7} times of the linear reflectance.

2 Results and discussion

Time dependence of the pump-probe signal is out of the scope of this paper. We discuss only a spectral dependence of the signal presented in Fig. 2. This dependence looks like an intense oscillations with almost constant period of ≈ 6.5 nm. We have confirmed by the additional experiments that these oscillations are not caused by the light interference. All these experiments led us to the conclusion that we observe the Franz-Keldysh oscillations (FKO). To verify this supposition the sample QDP1779 was supplied with electric contacts and electroreflectance spectrum was recorded with the field modulation frequency 100 kHz. It is also presented in Fig. 2. One can see exactly the same period of oscillations.

FKO are the evidence of the built-in electric field in heteroctructures containing InP QDs. We investigated photoreflectance spectra of structures without QDs (with 6000 Å of InGaP barrier layer, with GaAs quantum well between GaInP barrier layers) and also structures with InAs QDs between GaAs barrier layers. Spectra of all these structures lack any regular oscillations. Therefore existense of the built-in electric field is caused by presence of InP SADs in the structure.

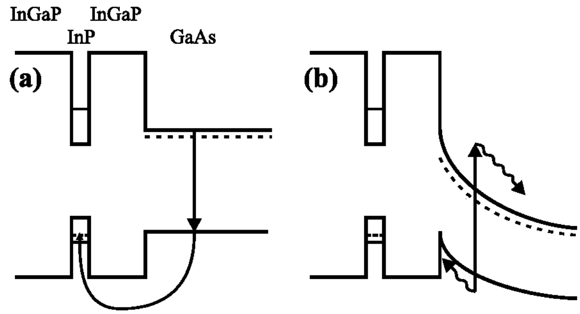

Fig 3. Charge transfer during structure growth (a) and photoreflection (b).

2.1 Model

We offer the following model of the energy structure and the physical processes which give rise to this electric field. The interface between QDs and barrier layers contains a large number of intrinsic defects which act as effective carrier traps. We suppose that these traps are mostly acceptors. GaAs buffer layers of the investigated structures contain donors whose density is about few times of 10^{15} cm^{-3}. During the growth process, a high temperature ($\approx$ 500 °C) gives to the electrons provided by donors enough energy to jump over the barrier between the buffer layer and QDs. As a result a surplus negative charge goes into the QDs layer and opposite charge into the buffer layer. This forms a double electric layer with electric field inside. Due to the small donor concentration in the GaAs buffer, the carrier depletion occurs over considerable thickness of this layer and the electric field partially penetrates into it. The model described is schematically drawn in Fig. 3.

This model is capable of explaining main features of the signal. In the spectral region in question the photorefractive signal is caused mainly by nonlinear reflection from the GaAs buffer layer. Pump pulses produce free carriers in this layer. Their motion changes the electric field and therefore the refractive index at the given wavelength. Essentially we observe changes in the FKO phase.

In order to determine the value of built-in electric field we made semiquantitative analysis of the FKO. We utilized an approximated formula of Aspens [5]

$$E(m) - E_g = \hbar\theta \left[\frac{3}{4}(m\pi - \varphi)\right]^{2/3}, \qquad (1)$$

where electrooptical energy is given by

$$\hbar\theta = \left(\frac{e^2\hbar^2F^2}{2\mu}\right)^{1/3}. \qquad (2)$$

Here $E(m)$ is the energy position of the m-th maximum, $E_g = 1.52$ eV — GaAs bandgap, φ — fitting parameter, and μ — reduced mass. We have gotten considerable deviation of the fitting curves $E(m)$ from the experimental curves for all studied samples which let us only approximately estimate magnitude of the field to be about 30 kV/cm. We suppose that this discrepancy is caused by the inhomogenity of the electric field in the GaAs buffer layer. Possible reason of this inhomogenity is distributed charge of the ionized donors in GaAs.

Obtained magnitude of the electric field allows us to estimate the surface charge density by the plane capacitor formula $\sigma = \varepsilon\varepsilon_0 F$. For the structures studied, it yields a charge of about 20 e per QD. Such a large amount of charge changes the physical properties of InP QDs and should be taken into account in their investigations.

It should be mentioned that the electric charge of the InP QD layer was observed by S. Anand *et. al.* by DLTS technique [6]. However they studied samples with Si-doped GaInP barrier layers. In their structures electric charge of QDs is caused by the electron transfer to the potential well from the barrier layers. This charging is not related to existence of GaInP/InP interface defects.

3 Conclusion

This research shows that in the heterostructures with InP QDs the interface between QDs and InGaP barrier layers contains a number of defects which behave like acceptors. During the growth process at high temperature they capture electrons from other layers of the structure. This gives rise to the intrinsic electric field. The field caused strong FKO which are observed in photo- and electroreflection spectra. We discovered that in the investigated structures there is negative charge of about 20 electrons per QD. This charge essentially affects the physical properties of the QDs and should be taken into consideration in their studies.

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